# Innovative Beam Physics for High Luminosity at Hadron Colliders

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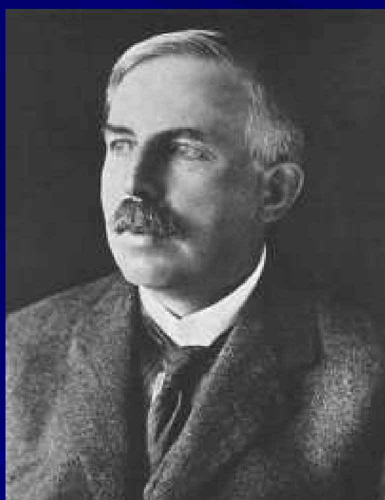
# Why do we need High Energy Accelerators?

- To explore the fundamental nature of Energy, Matter, Time and Space

  The earliest particle beam experiment used to study the structure of "then fundamental" particle, "atom", was by Rutherford in 1909



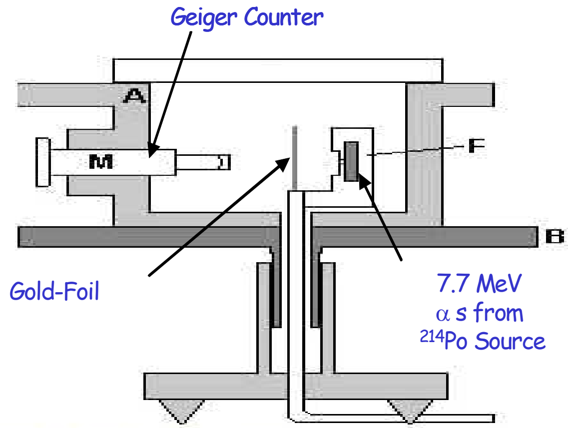
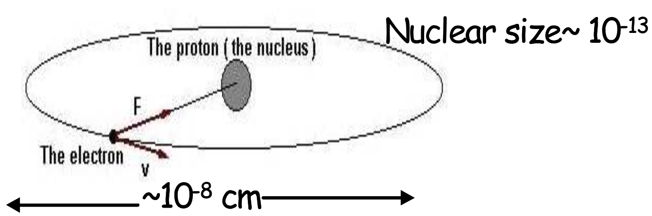
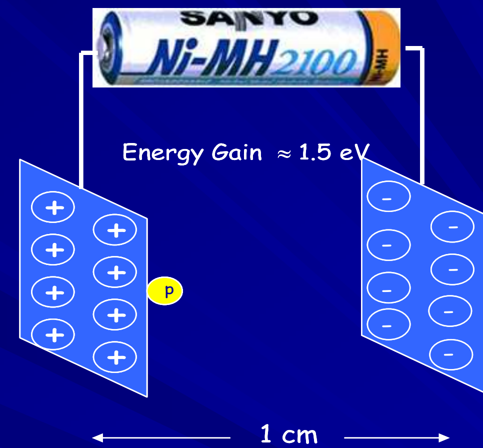



Fig1. Marsden-Geiger experiment.

**Conclusions:**




1 eV = 1.602e-19 Joule
=3.829e-20 Calorie

1 MeV = $10^6$eV
= 1.602e-13 Joule
=3.829e-14 Calorie

1 TeV = $10^{12}$eV
= 1.602e-7 Joule
=3.829e-8 Calorie

Stored Energy at

Tevatron ≈ 2MJ

LHC ≈ 360MJ!!!

# HEP Particle Accelerators are Monstrous Microscopes!!!

The resolving power of a microscope = $1.22\lambda$

From de Broglie, the wave-length associated with a particle of momentum p

$$\lambda = h/p$$

Therefore

- To resolve the nucleus of hydrogen atom (size~$10^{-13}$cm) we need beam of momentum ~200 MeV/c
  (ref. Rutherford 1909: alpha scattering off nucleus
  Hofstadter 1956: Measurement of nuclear size → 190 MeV electron scattering)

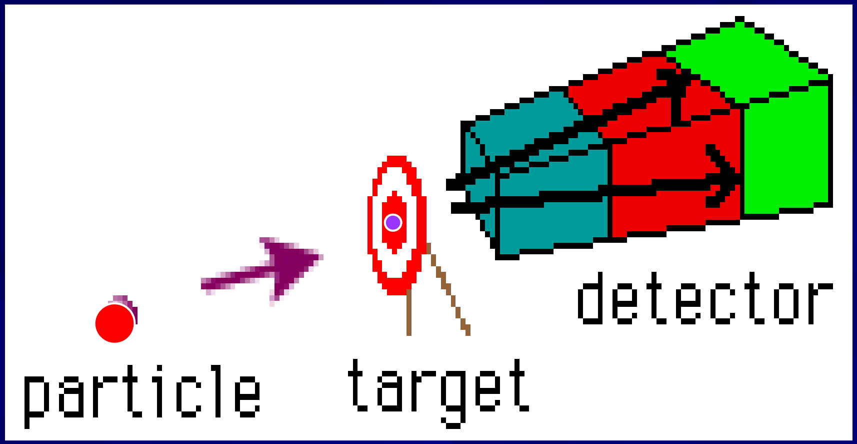
- To probe the structure of individual nucleons (distance scale ~$10^{-15}$cm) we need beam momentum ~Tens of GeV/c
  (ref.: Friedman, Kendall and Taylor, 1967, 20 GeV e- beam at SLAC)

Current length scale being probed $\leq 10^{-16}$ cm

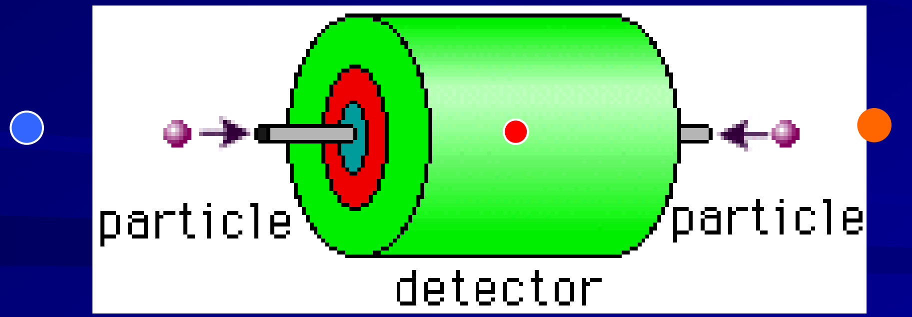
**Important factors in HEP Accelerators:**
**→ Energy of the Particle-Beam**
**→ Intensity of the Particle-Beam**

# Fixed Target vs Colliders

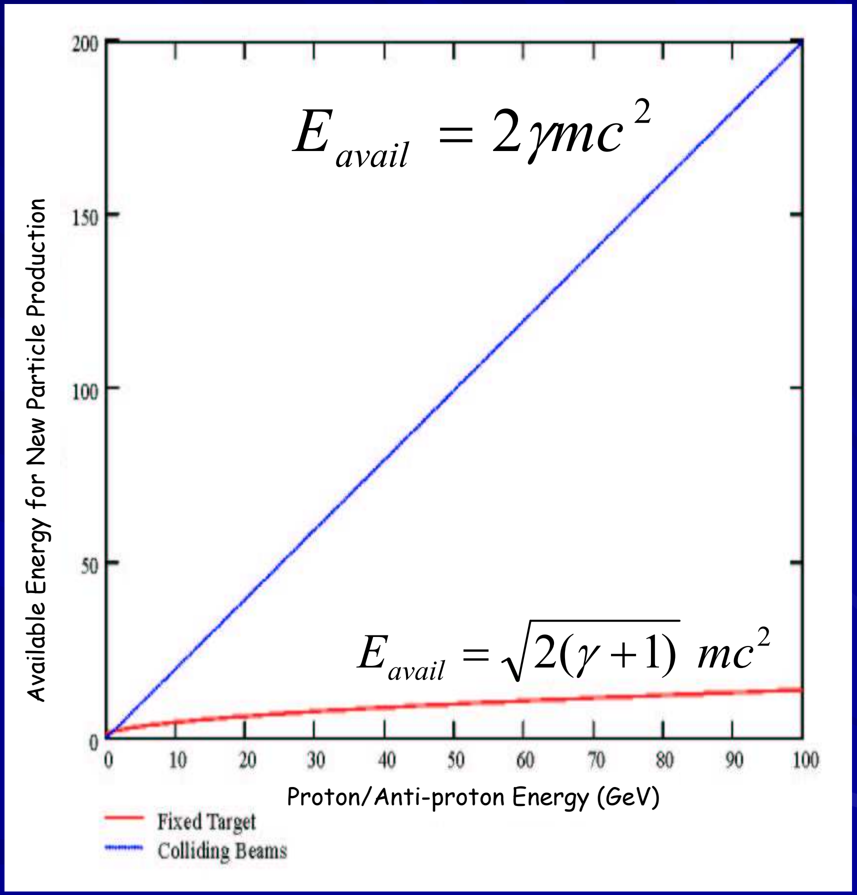
Fixed Target HEP Experiments




Colliding Beam HEP Experiments



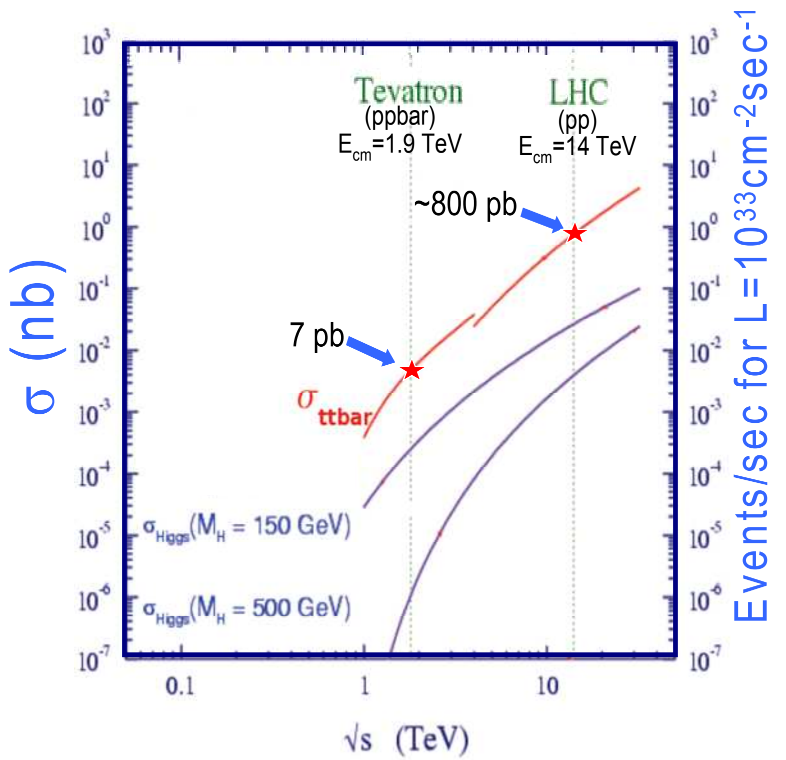

From Relativistic Kinematics




Colliders have advantage over fixed target scenario

# HEP Event Rate as a function of Collider Energy and Luminosity

Production cross section vs Beam Energy




\# of Events for a HEP Process

= Probability for the Process $\times \int L dt$

Where Luminosity

$$L = f_{collision} \frac{N_1 N_2}{4\pi r^2}$$

$r$ = transverse beam size,
$N_1$ = Number of particles of type 1
$N_2$ = Number of particles of type 2
$f_{collision}$ = Number of collisions/sec

Increasing beam Energy is very Expensive

Increasing beam intensity and its quality need innovative beam manipulation

# Beam Quality

- Attributes characterizing the beam quality
  - Emittance is total phase-space (6D) area occupied by all beam particles. It is a measure of **Transverse** and **Longitudinal** temperature of the beam.
    - Transverse emittance ($\pi$-mm-mr)

$$\varepsilon_x = \frac{r^2}{\beta_x}$$

    - Longitudinal emittance (eVs)

$$LE(rms) = \pi\,\Delta\,\mathrm{E(rms)}\,\mathrm{RMS}_{\text{Bunch Length}}$$

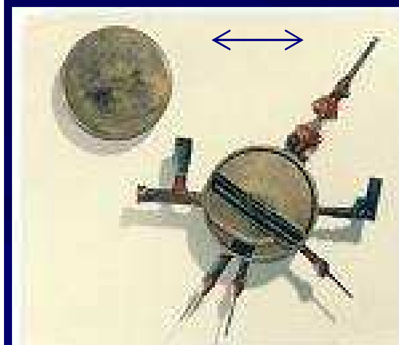
  - Beam intensity ← Number of beam particles

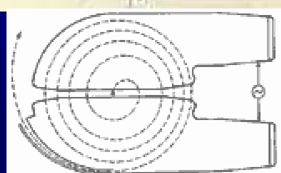
We need high beam intensity and small emittances

# “Livingston Plot”

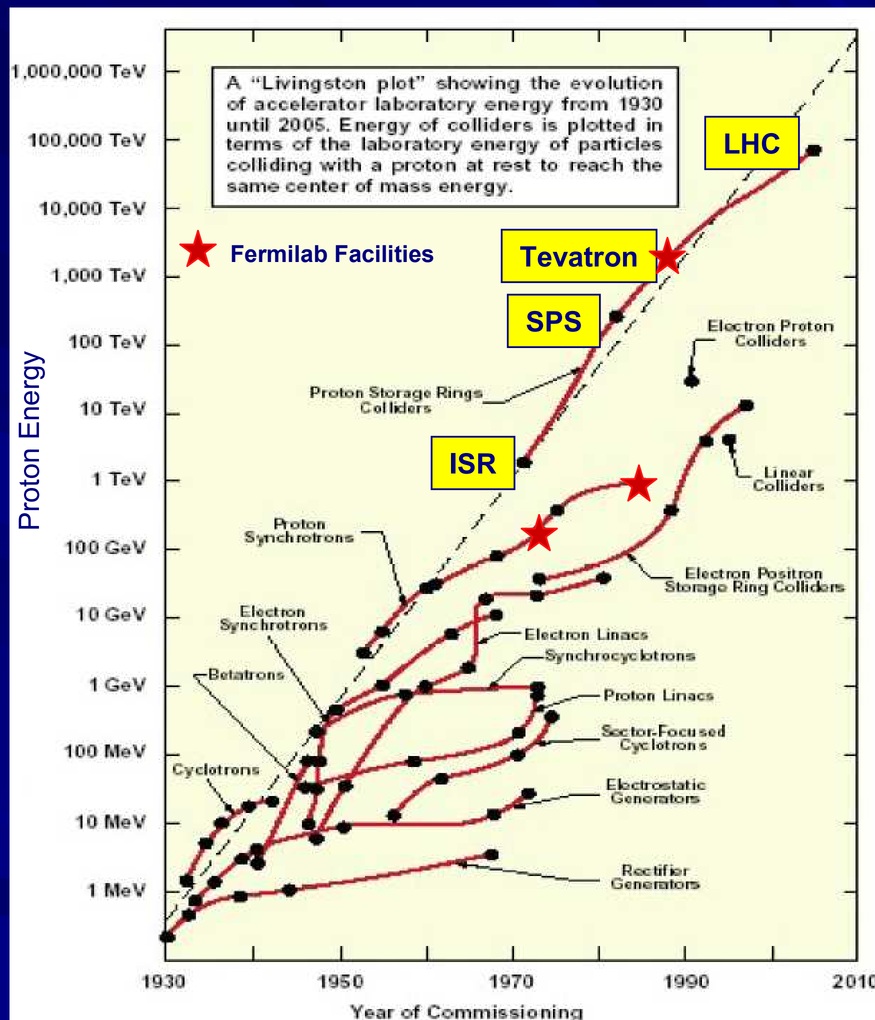
## Particle Energy vs Year of machine commissioning

4.5 in.





**Earliest Circular Accelerator**
by *E.O. Lawrence, 1931*




5 TeV $\mu^+\mu^-$ Collider

Higgs boson
& many more??

t-quark

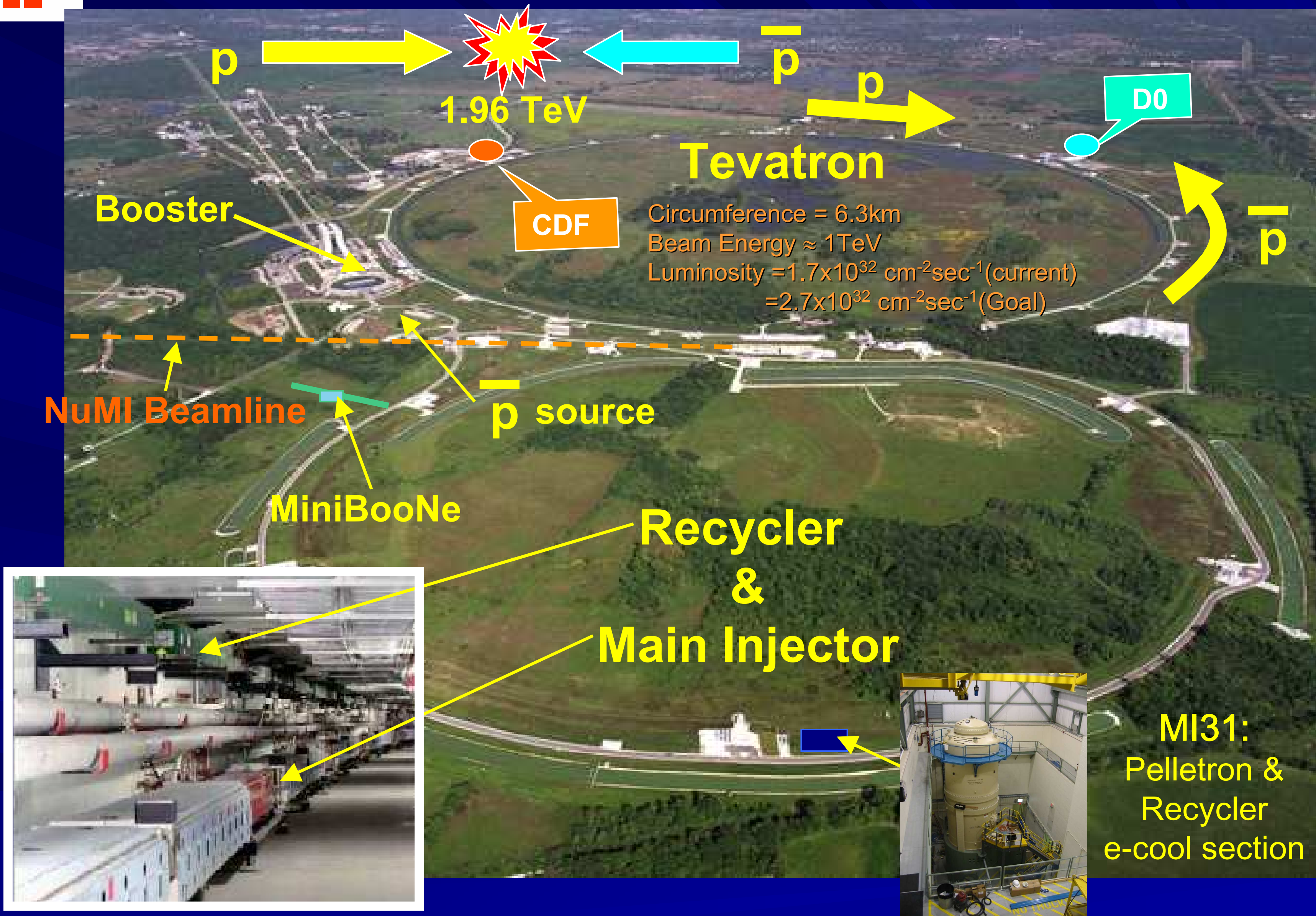
W, Z-bosons

b-quark

c-quark

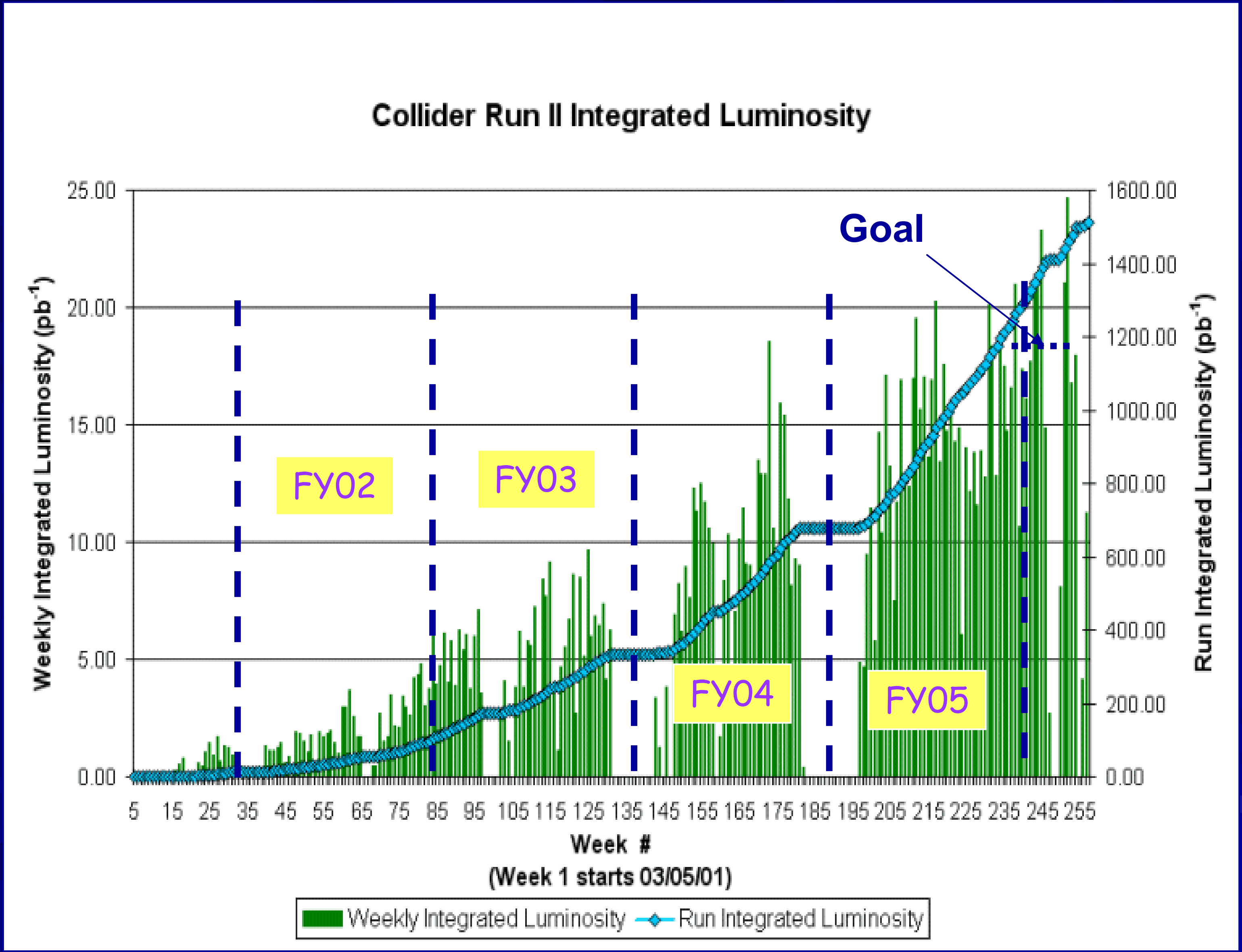
s-quark

# World’s Pre-eminent HEP Laboratory



# Tevatron Parameters

| | |
|---|---|
| Ring Circumferences = | 6.4 km |
| Number of Proton bunches = | 36 |
| Number of Pbar bunches = | 36 |
| # of protons/bunch = | $2.4 \times 10^{11}$ (goal, $2.7 \times 10^{11}$) |
| # of pbars/bunch = | $0.7 \times 10^{11}$ (goal, $1.4 \times 10^{11}$) |
| Proton Trans. Emit. = | 16 $\pi$ mm-mr |
| Longitudinal Emit = | 4 eVs (@ collision) |
| Pbar Trans. Emit. = | 6-10 $\pi$ mm-mr |
| Longitudinal Emit.= | 4 eVs (@ collision) |
| Beam-Beam tune shift = | 0.025 maximum |
| Tunes = | 0.583 (H), 0.578 (V) |
| Luminosity life time = | 7-8 hr |



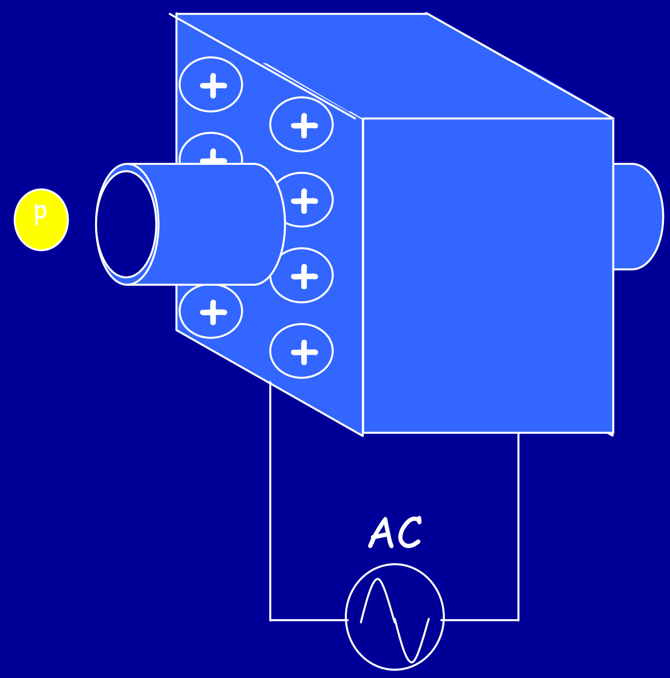
Collider Run II Integrated Luminosity
Goal
FY02
FY03
FY04
FY05
Weekly Integrated Luminosity (pb-1)
Run Integrated Luminosity (pb-1)
Week #
(Week 1 starts 03/05/01)
Weekly Integrated Luminosity
Run Integrated Luminosity

# Novel Beam Manipulation Techniques for Collider Run II and other HEP Experiments

Many of the techniques are based on RF beam Gymnastics

# What is an Accelerator RF Cavity?

Pill-box cavity



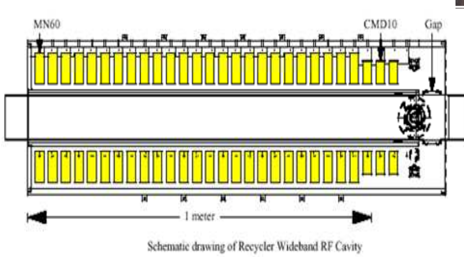
# RF cavities in use


MI 53MHz RF cavity


MI 2.5MHz RF cavity
(Coalescing RF cavity)


MI Damper RF cavity
(Broad Band Cavities)

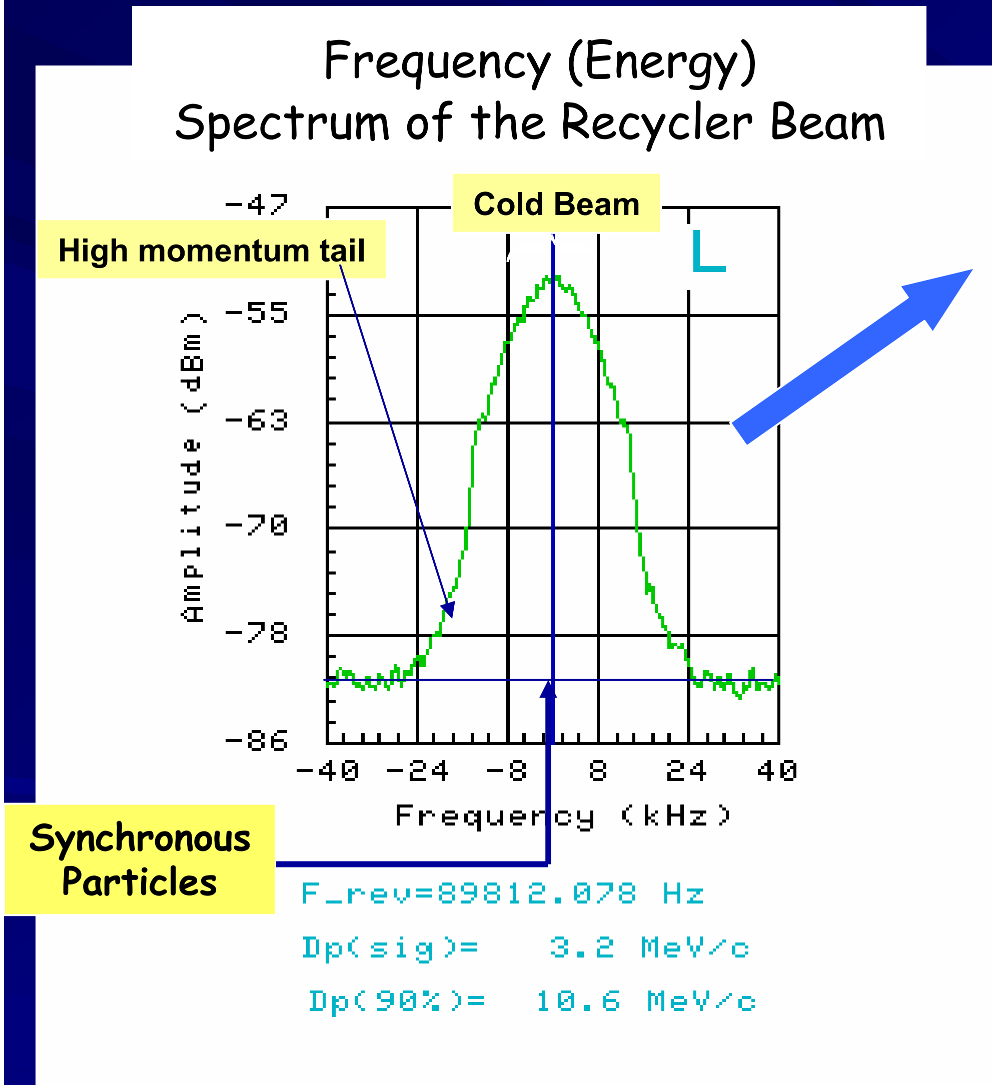

Finemet MI Damper RF cavity
(Broad Band Cavity)

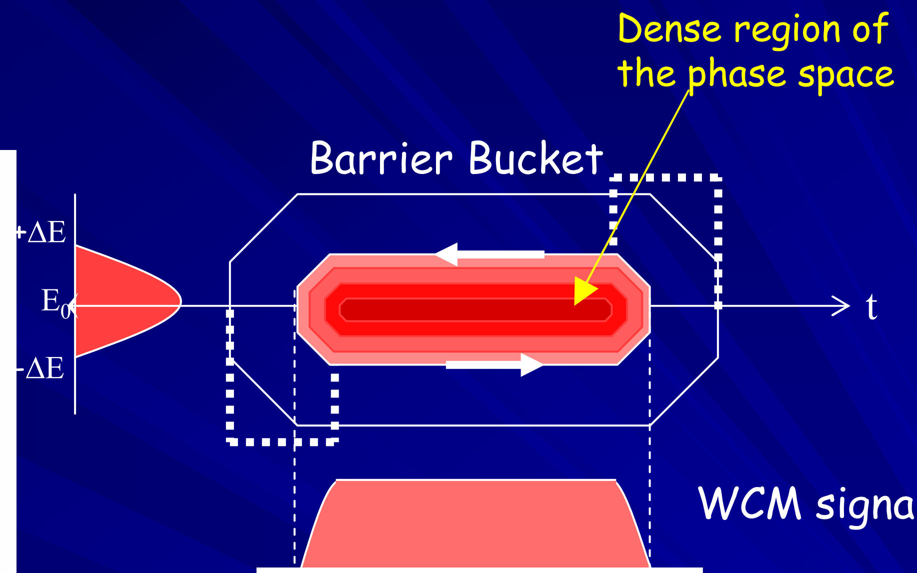




Recycler RF cavity
(Broad Band Cavities)

# Momentum Mining

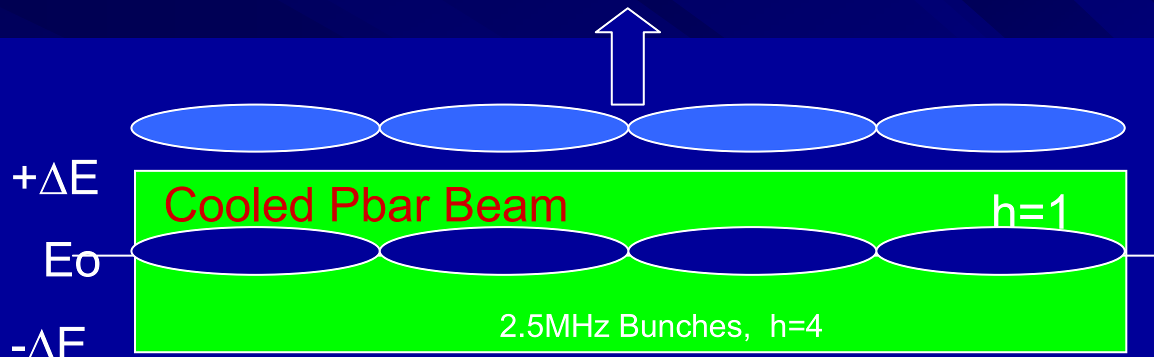


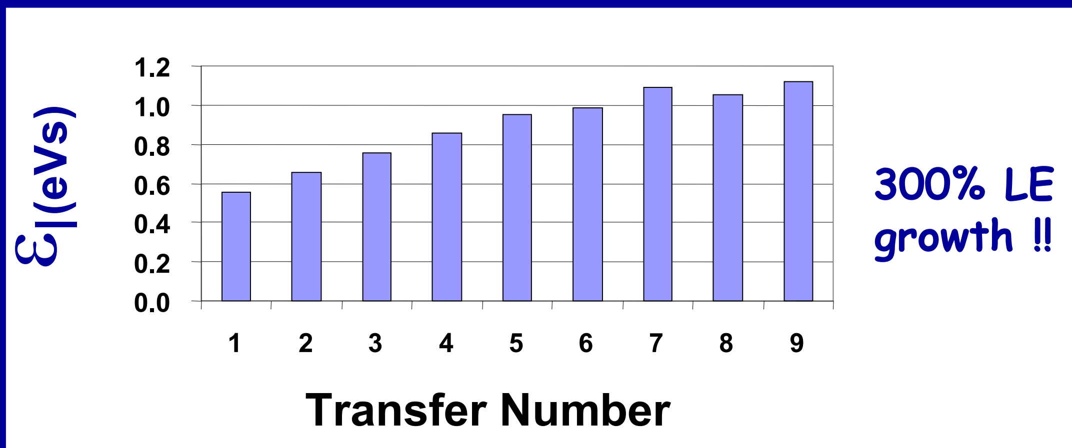



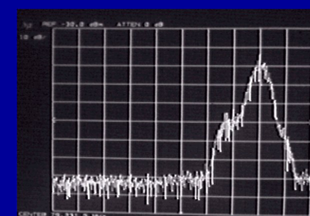

Is it possible to isolate the cold beam from the high momentum tail of a beam distribution without emittance growth and use only the cold beam and use the leftover hot beam after further cooling?

# Transverse Momentum Mining

## (Current Mining Scheme at the Fermilab Accumulator)

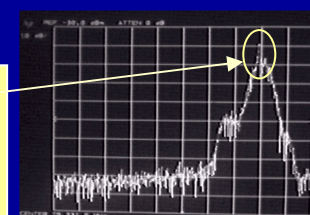


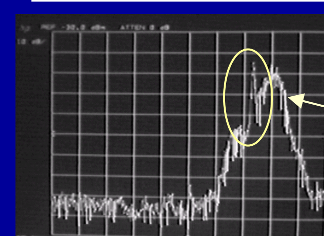



195E10 pbars Cooled Beam (12.7 eVs)

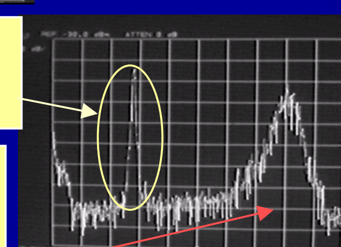
1st extraction from the core ≈ 3 eVs





Away from the core

Beam close to extraction orbit



174E10 pbars 12.4 eVs,22% growth

- **This is the method used in all hadron storage rings so far.**

# Longitudinal Momentum Mining in a Synchrotron

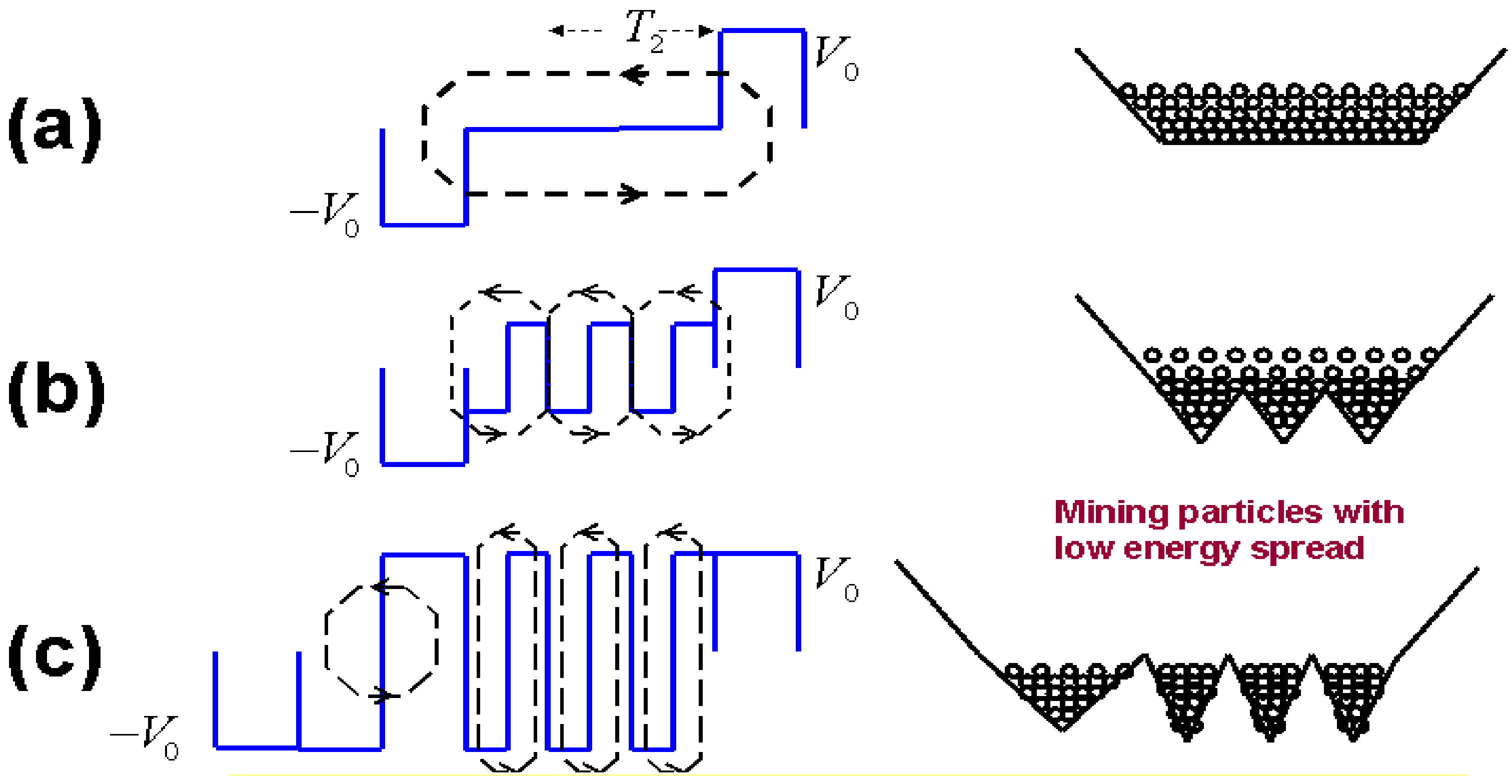
New Technique

Ref: C. M. Bhat, Phys. Lett. A 330 (2004) 481

## Physics

RF Voltage & Beam Boundary

Potential $U = \int V(t)dt$ & Beam Particle

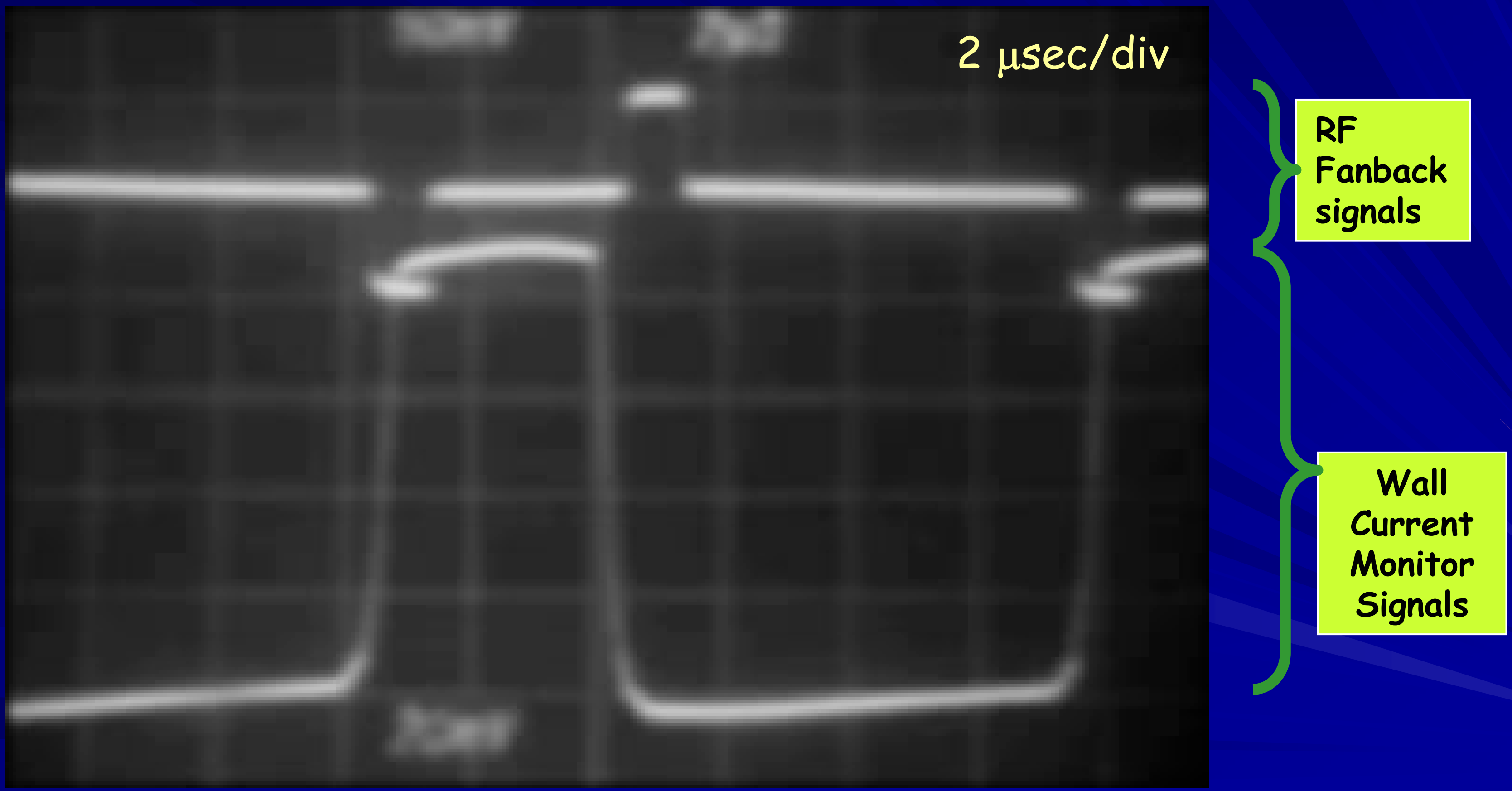



Technique is applicable to any storage ring for beam mining

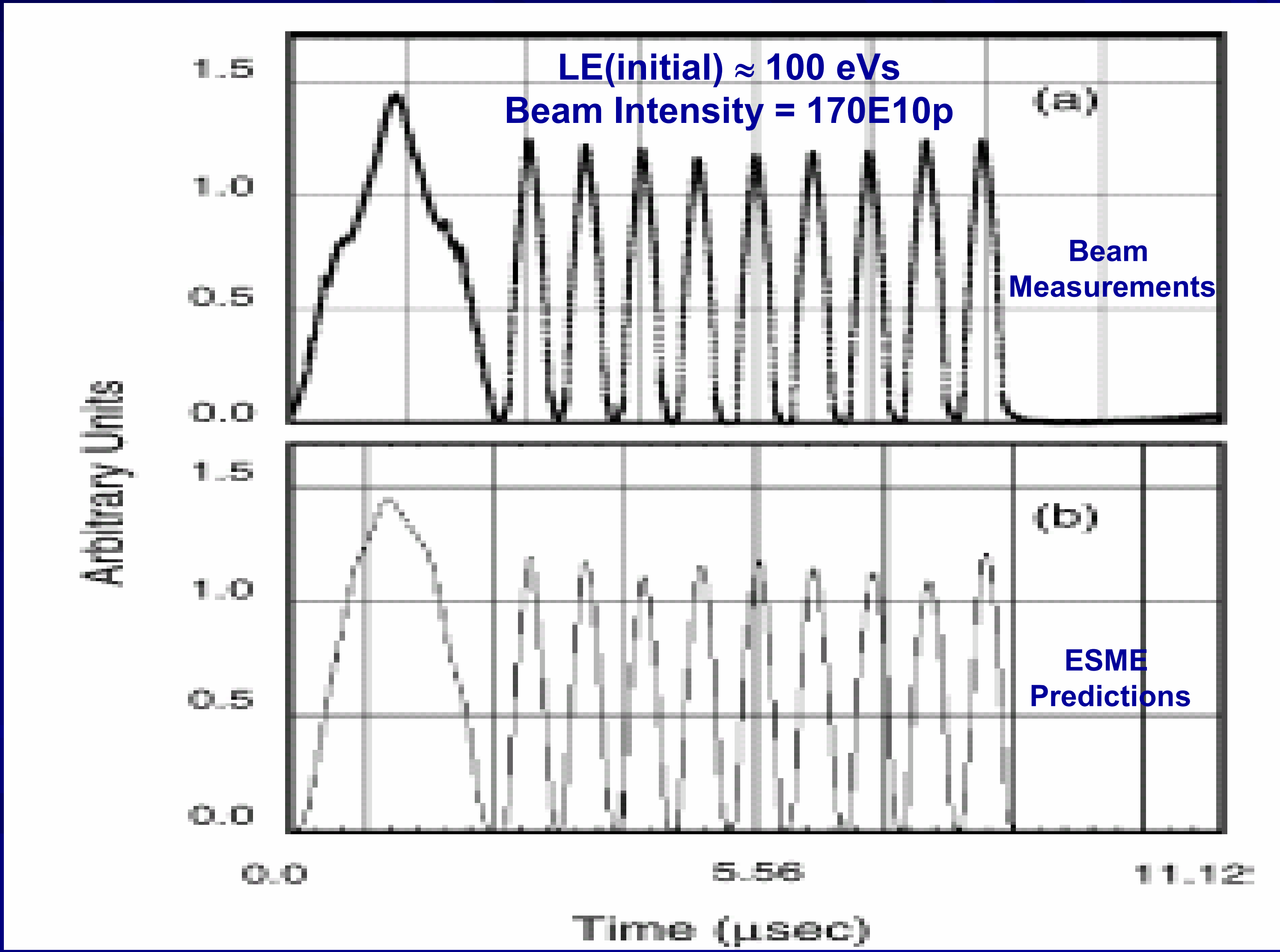
# Longitudinal Momentum Mining in the Fermilab Recycler

(proof of principle with protons)
Dec. 2003,

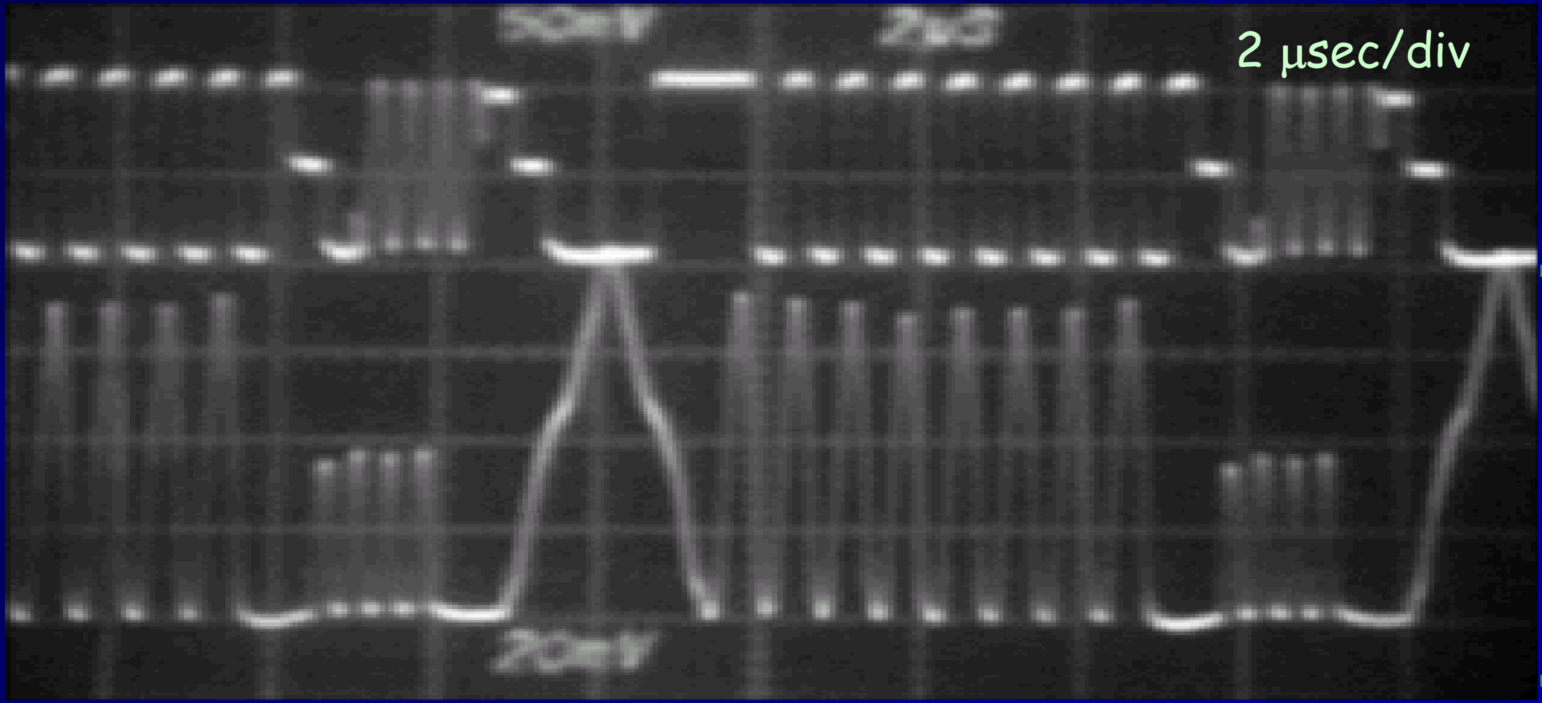
**LE(initial) ≈ 100 eVs**
**Beam Intensity = 170E10p**



# A Comparison between Measurements and Predictions



# Momentum Mining (cont.)
# Tevatron Collider Shots



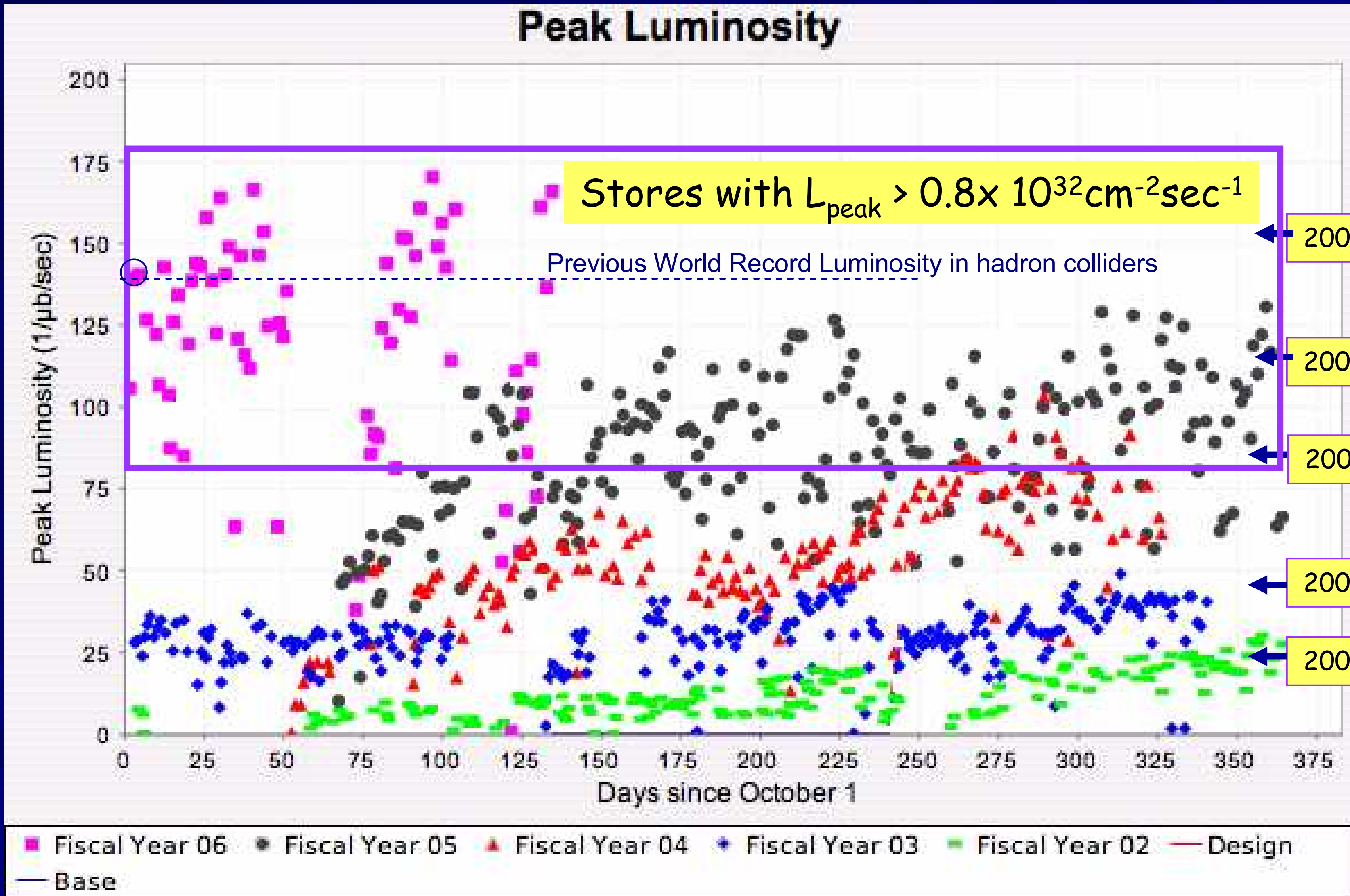

RF Fanback signals

Wall Current Monitor Signals

We are using this scheme since early 2004.

**Outcome** –All the ppbar collider stores in the Tevatron with initial L > 0.8 $\times 10^{32} cm^{-2} sec^{-1}$ came from longitudinal momentum mining in the Recycler.

# RESULTS



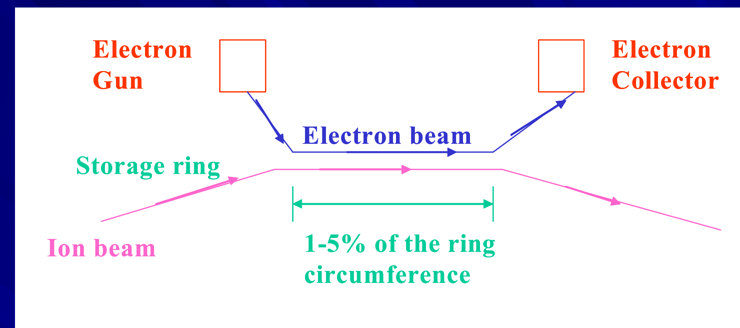
Peak Luminosity
Stores with $L_{peak}$ > 0.8x $10^{32}cm^{-2}sec^{-1}$
Previous World Record Luminosity in hadron colliders
2006
2005
2004
2003
2002
Peak Luminosity (1/µb/sec)
Days since October 1
Fiscal Year 06
Fiscal Year 05
Fiscal Year 04
Fiscal Year 03
Fiscal Year 02
Design
Base

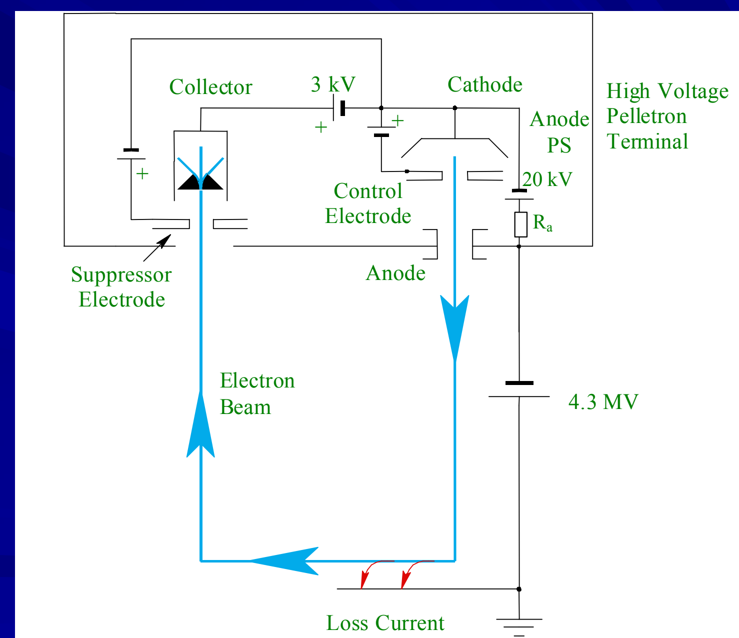
# Beam Cooling

- One of the most important development which made the ppbar colliders feasible is the invention of pbar cooling technique.

  - Stochastic Cooling (van der Meer, CERN, 1968) ← looked complicated but turned out to be first method used at ppbar collider

  - Electron-cooling (Invented by Gersh Budker, 1966) Demonstrated in 1976 for low energy rings← Looked very simple but it took about 29 years to make it useful for the ppbar collider



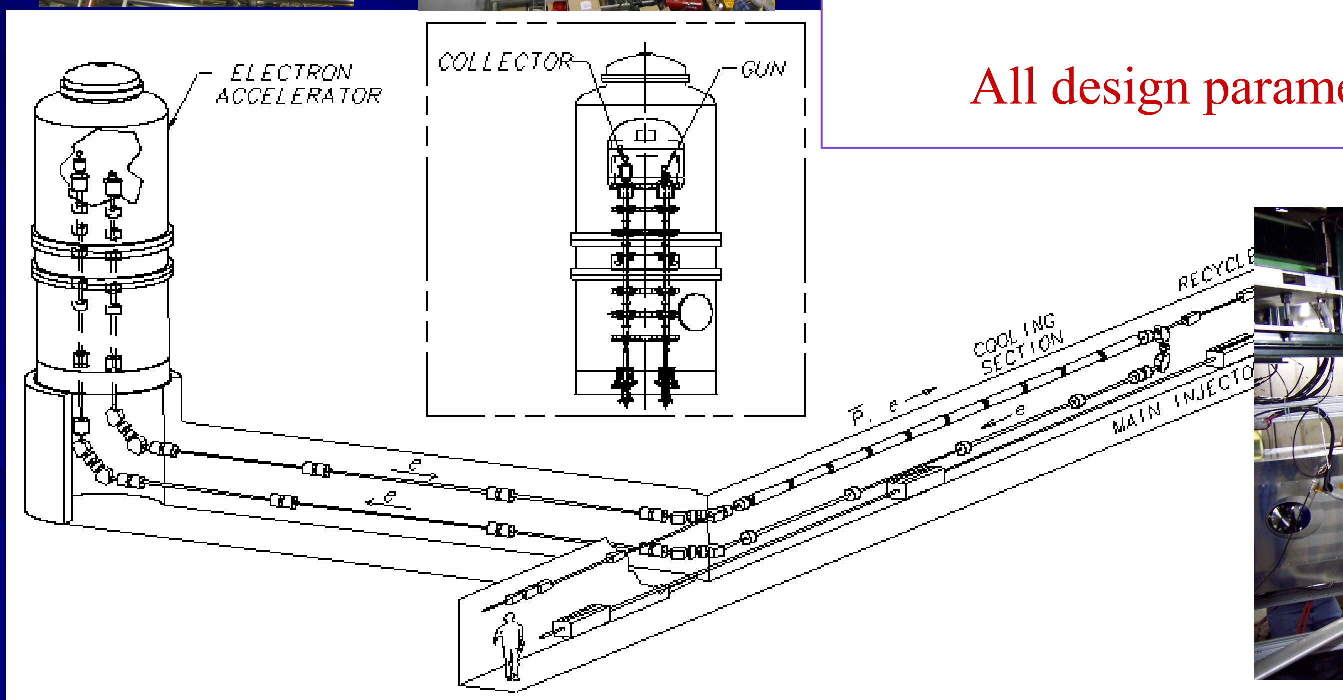




Fermilab is the first place in the world which now uses e-cooling of particle beams for HEP program.

# Recycler Electron Cooling

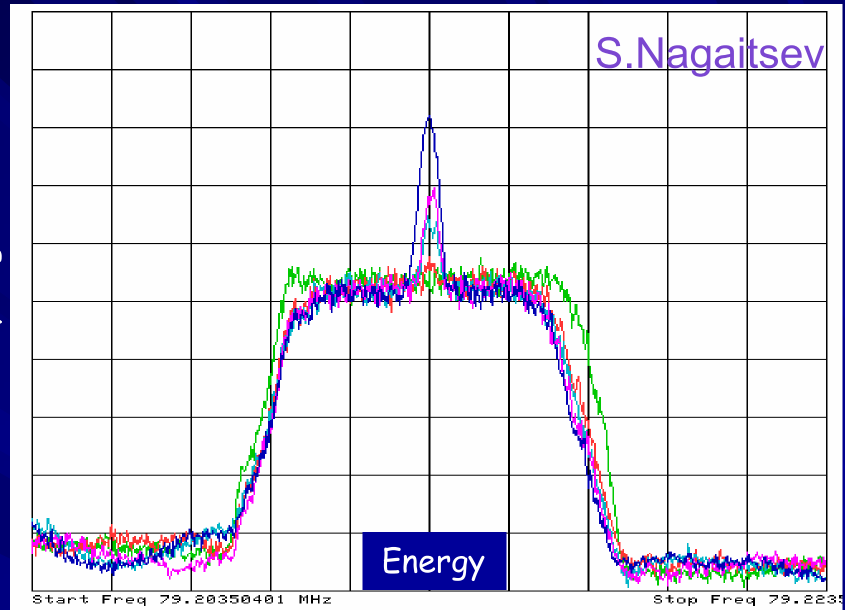
| | |
|---|---|
| Electron kinetic energy | 4.34 MeV |
| Uncertainty in electron beam energy | ≤ 0.3 % |
| Energy ripple rms | 500 V rms |
| Beam current | 0.5 A DC |
| Duty factor (averaged over 8 h) | 95 % |
| Electron angles in the cooling section (averaged over time, beam cross section, and cooling section length), rms | ≤0.2 mrad |

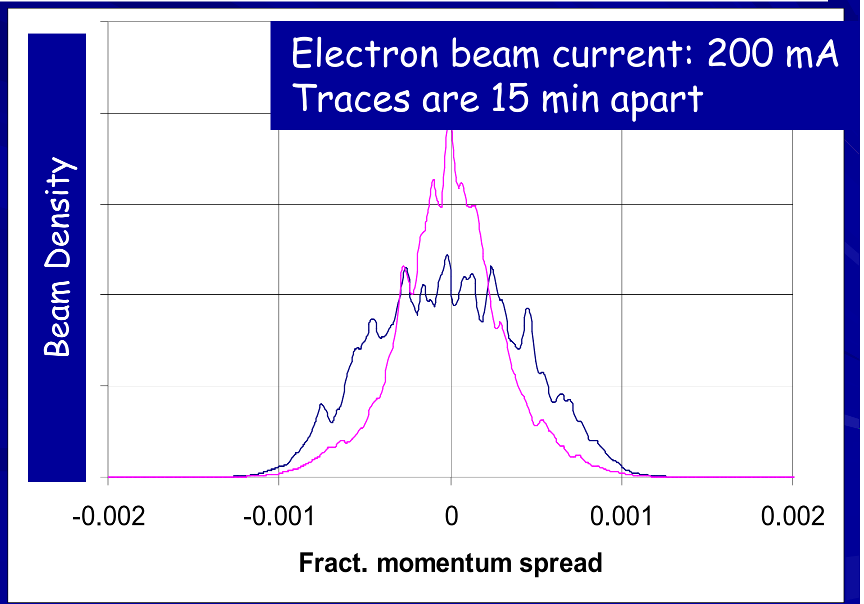
All design parameters have been met



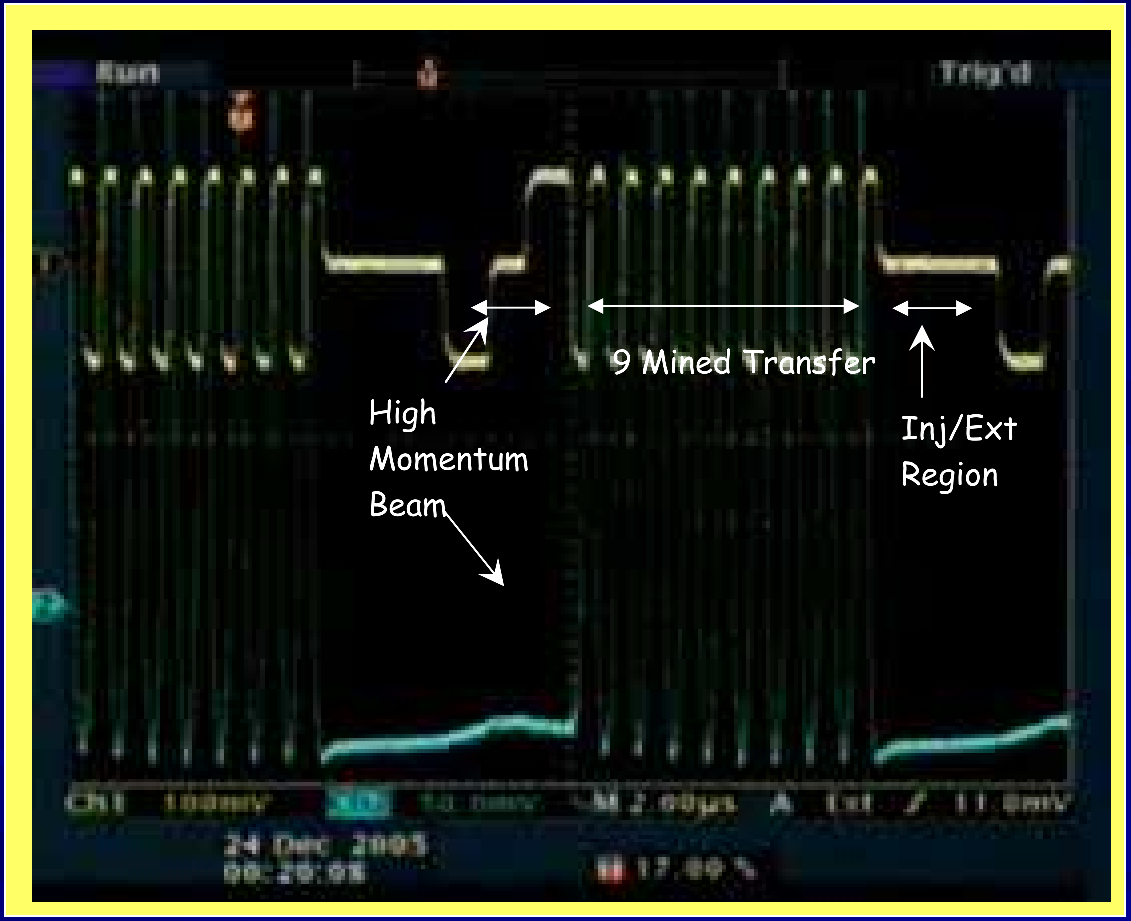

# Electron Cooling Commissioning (July 05)

- Electron cooling commisioning
  - Electron cooling was demonstrated in July 2005 two months ahead of schedule.
  - By the end of August 2005, electron cooling was being used on every Tevatron shot
- Electron cooling rates
  - Drag rate: 20 MeV/hr for particles at 4 MeV
  - Cooling rate: 25 $hr^{-1}$ for small amplitude particle
  - Can presently support final design goal of rapid transfers (30eV-sec every hour)
  - Have achieved 500 mA of electron beam which is the final design goal.



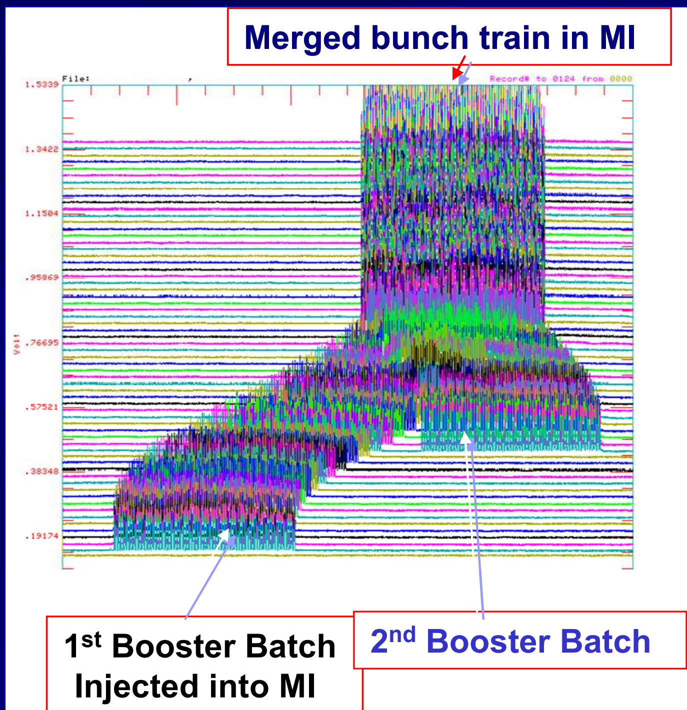
# Momentum Mining on e-cooled beam

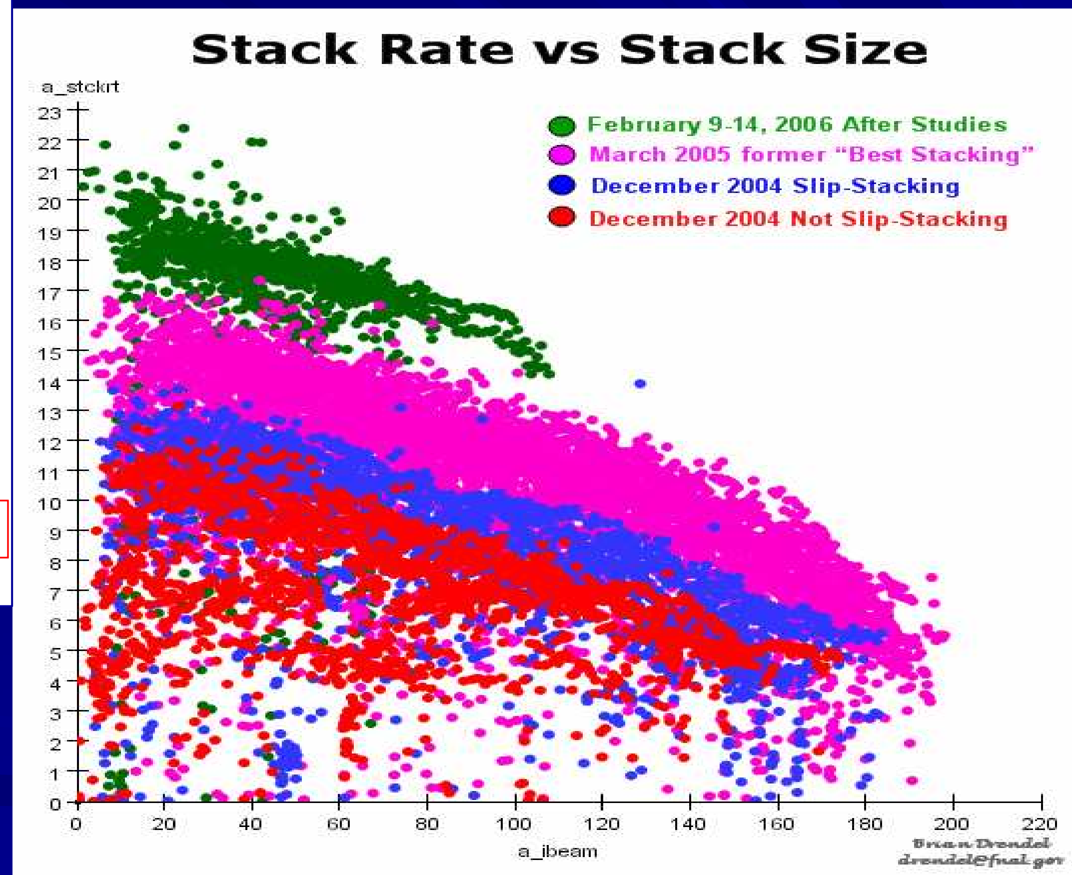



Now we routinely inject up to about 97% of the pbars to the Main Injector from the Recycler

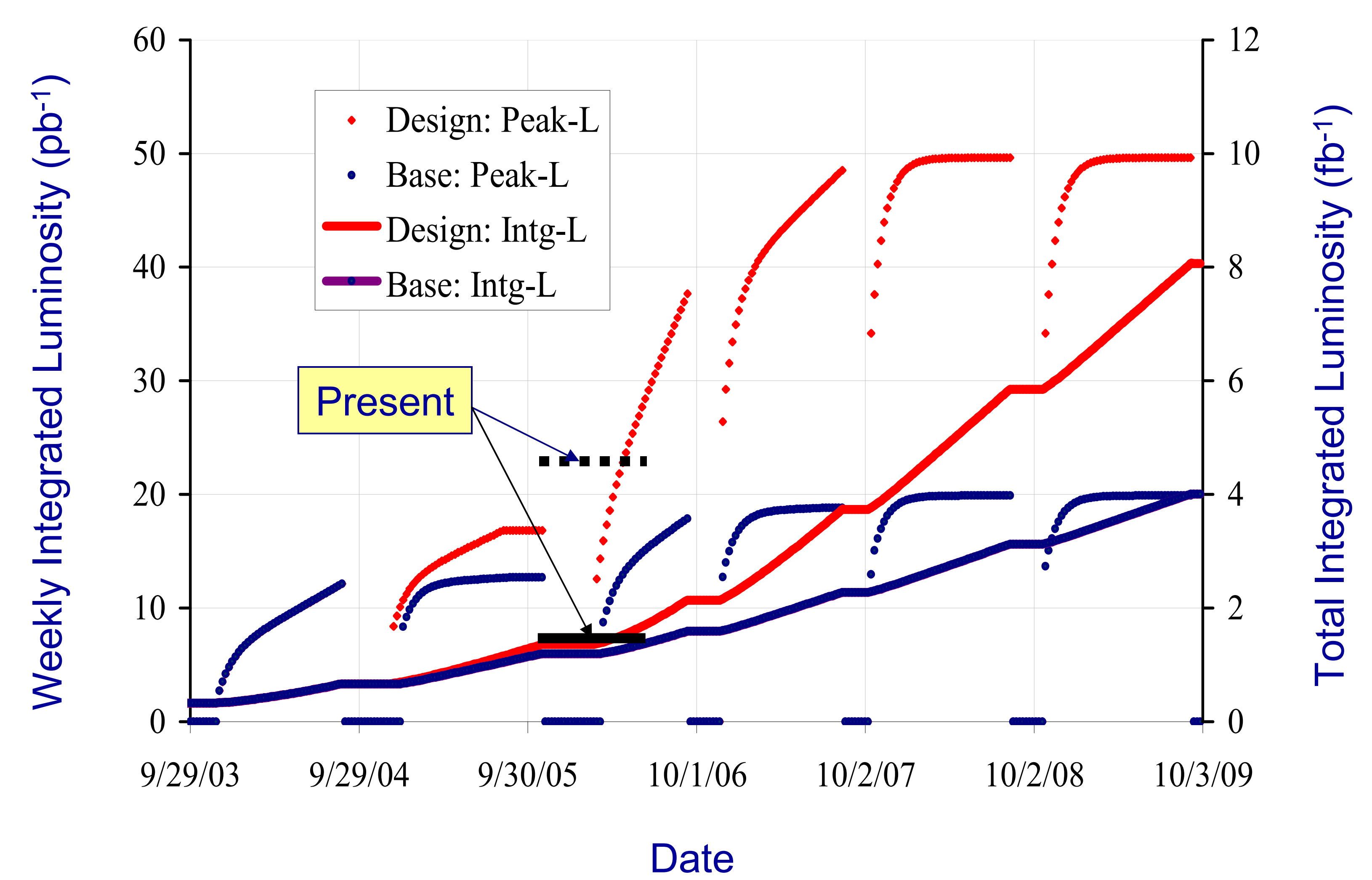
Imax(pbars) = 430E10
Goal = 600E10

# Slip stacking in the Main Injector to improve the Pbar Stacking Rate



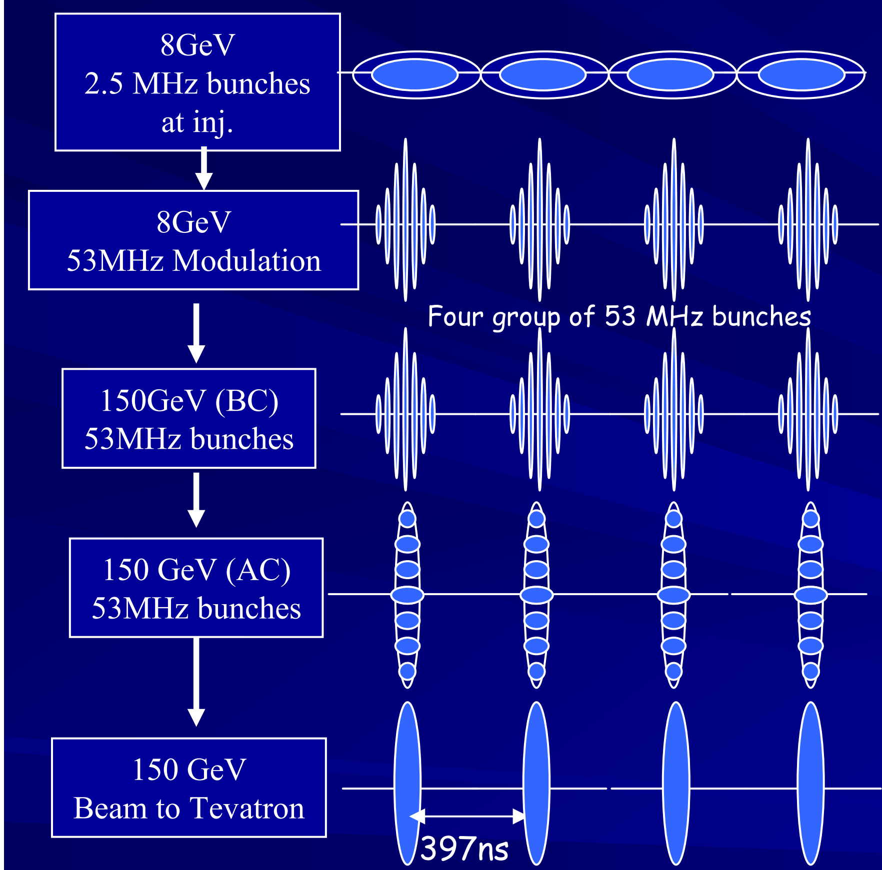



# Luminosity Projection



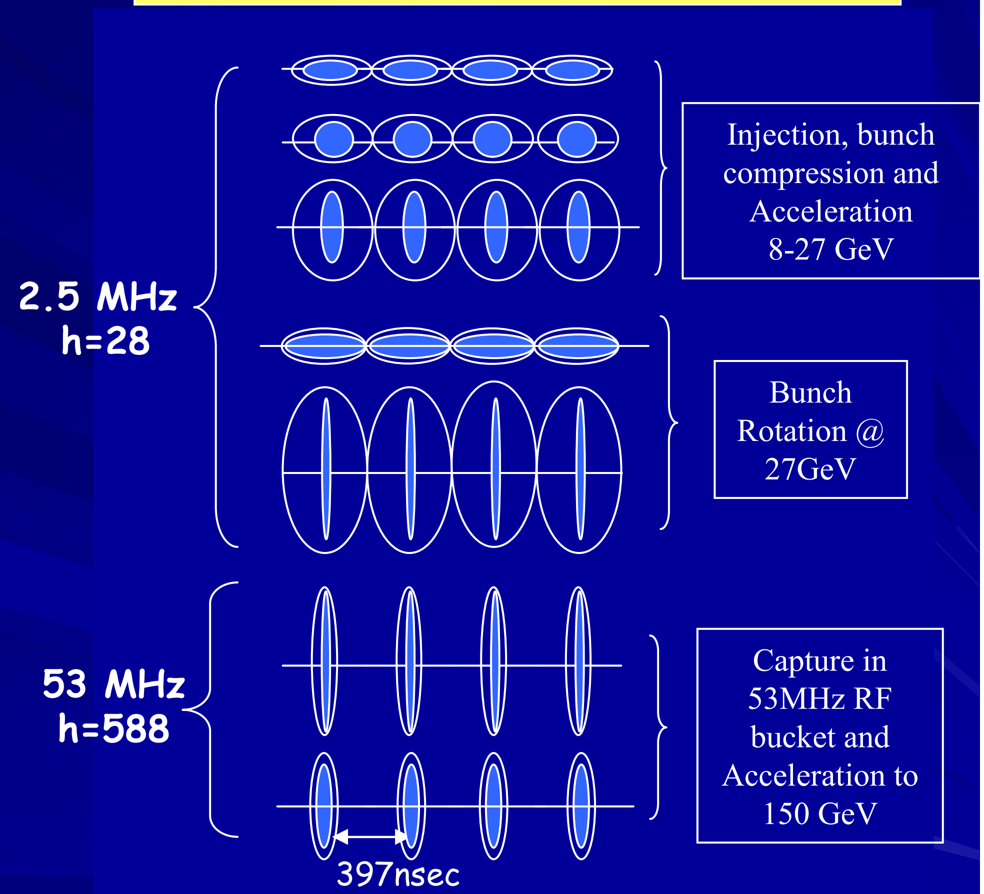
# Bright pbar Bunches for Collider Operation in the Main Injector

## Current Scheme



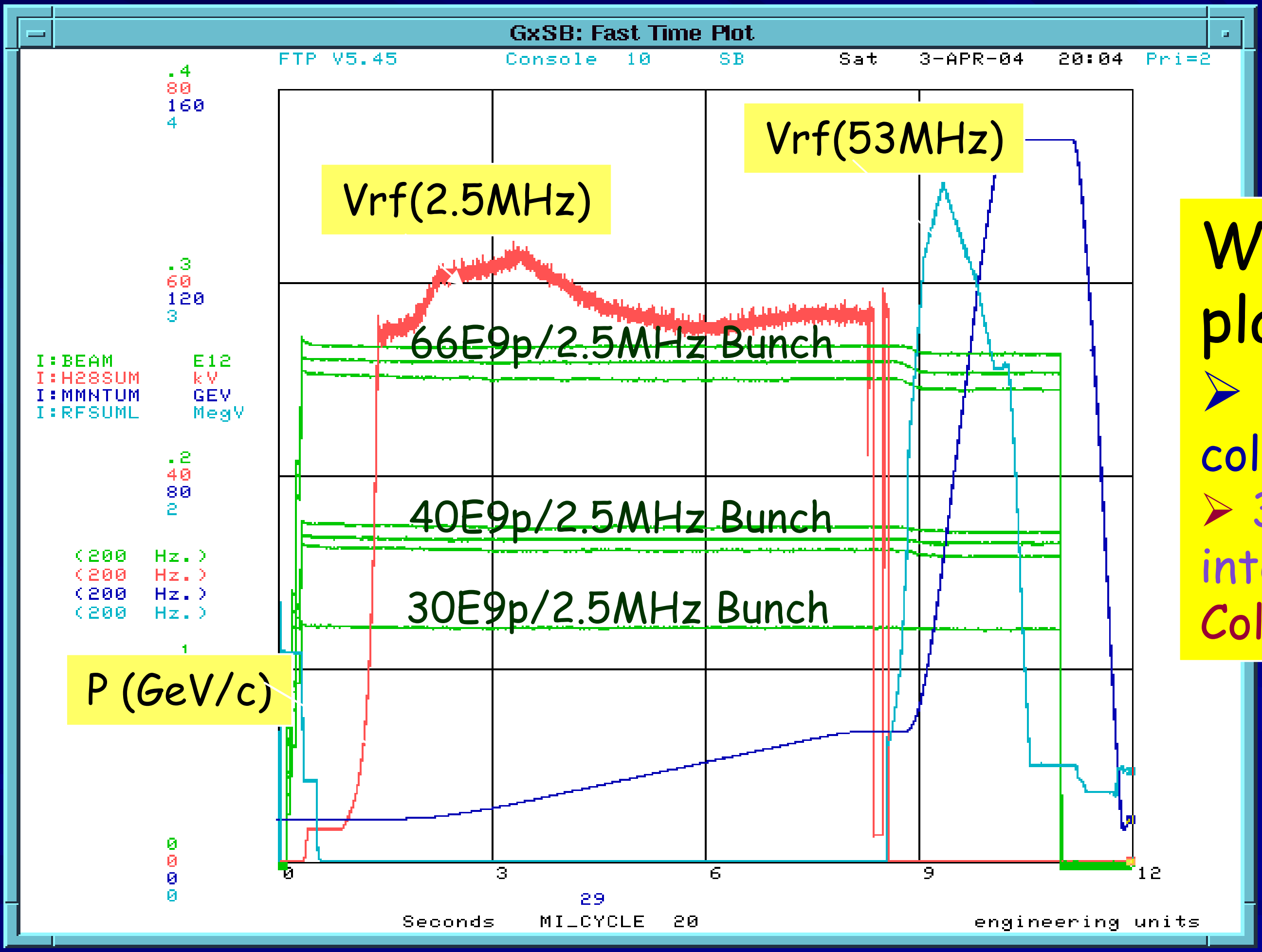

100% Longitudinal Emittance Growth and ≈20% pbar loss

## 2.5MHz Acceleration Scheme




Minimal Longitudinal Emittance Growth and No Beam Loss

# 2.5MHz Acceleration in the MI (proof of principle)




With this scheme in place one expects

- about 17% increase in collider luminosity
- 35% Shorter interaction region for the Collider Detectors

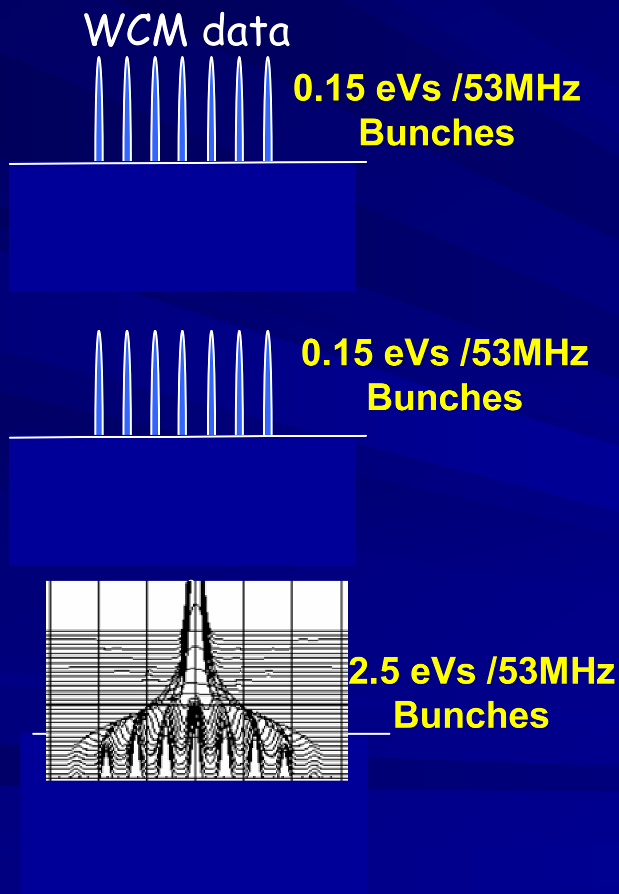
# Bright Proton Bunches for Future

Current Proton Bunch Coalescing Scheme in the Main Injector

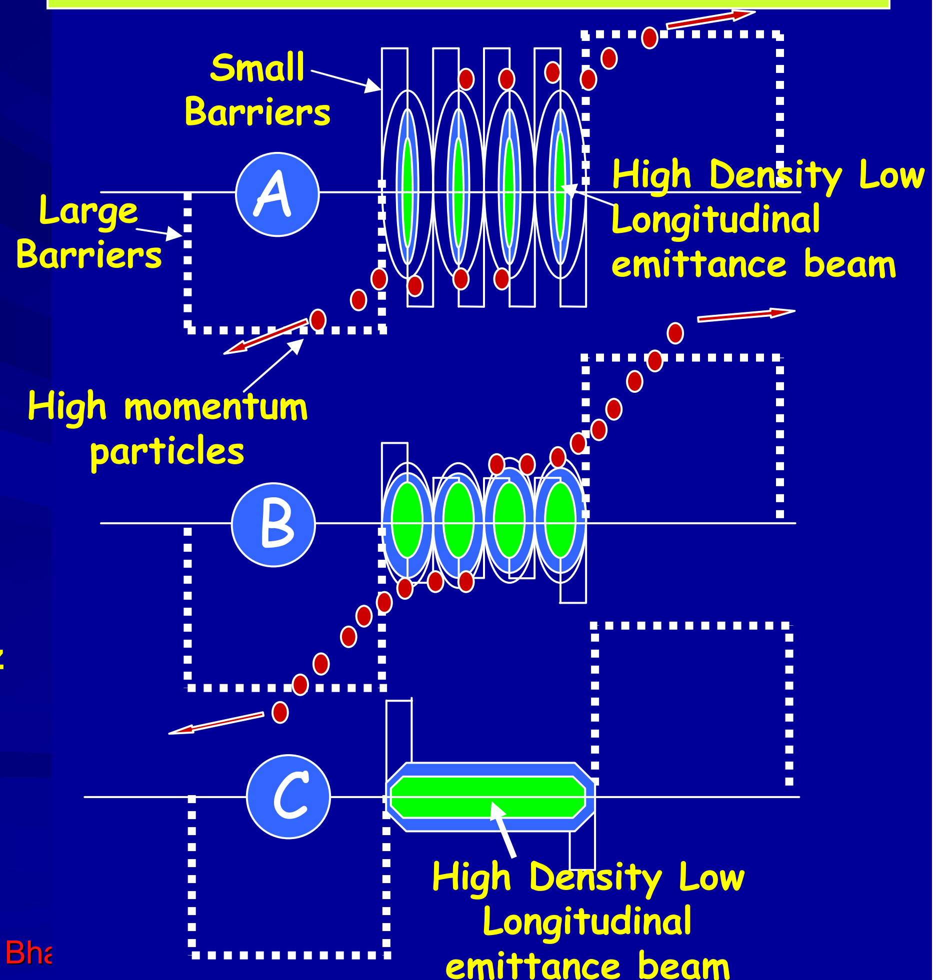
8GeV
53MHz Bunches

150GeV (BC)
53MHz Bunches

150 GeV (AC)
53MHz bunches

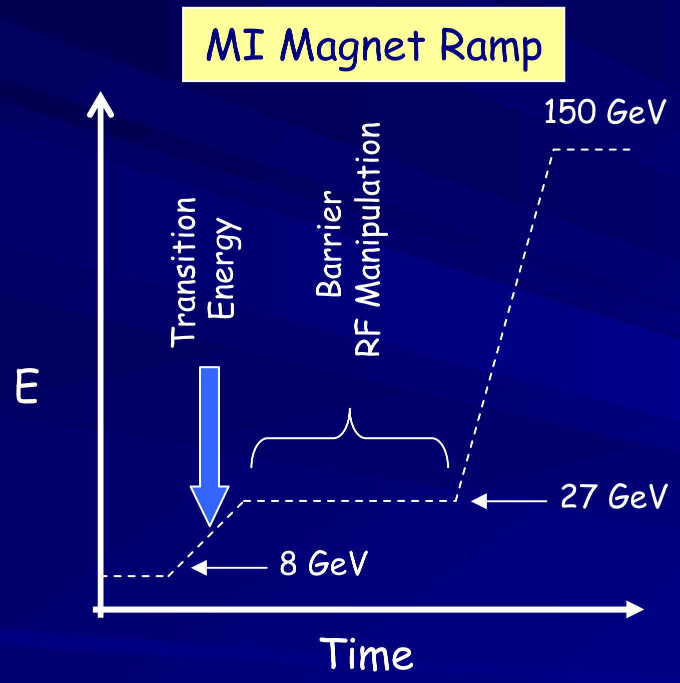


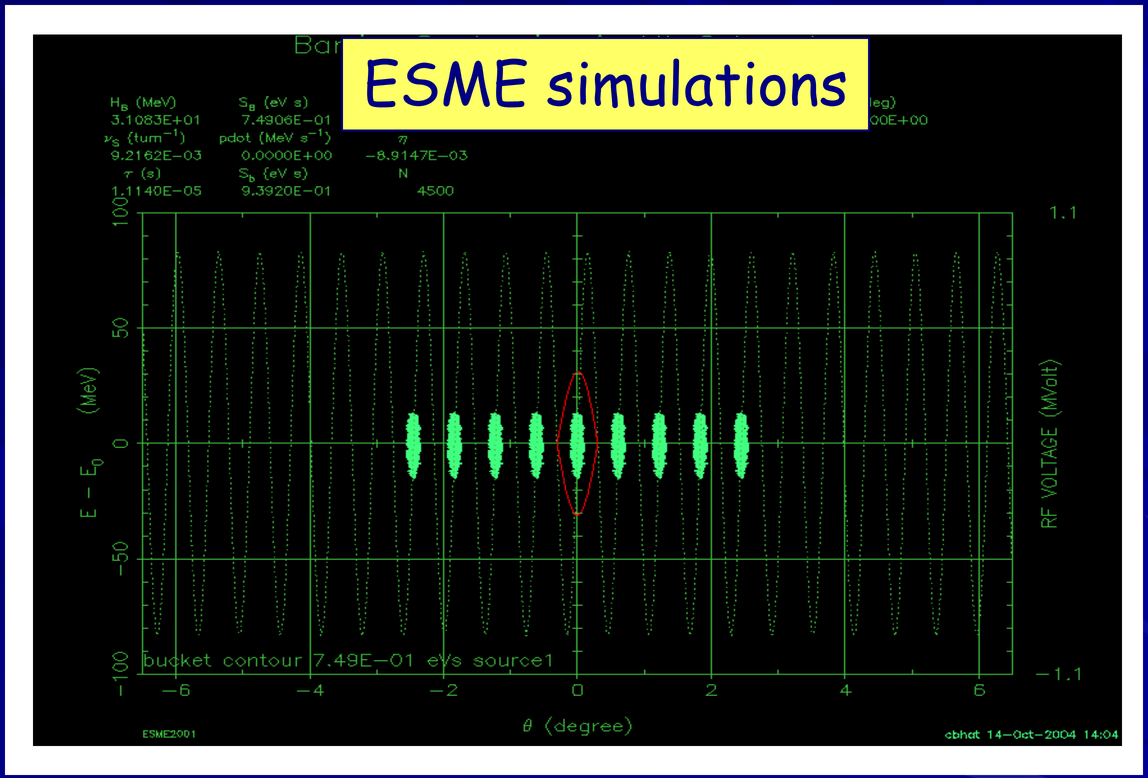

Proposed Barrier Proton Coalescing
Ref: FERMILAB-FN-0761-AD (October 2004)



# Bright Proton Bunches for Collider Shots

## MI Barrier Coalescing

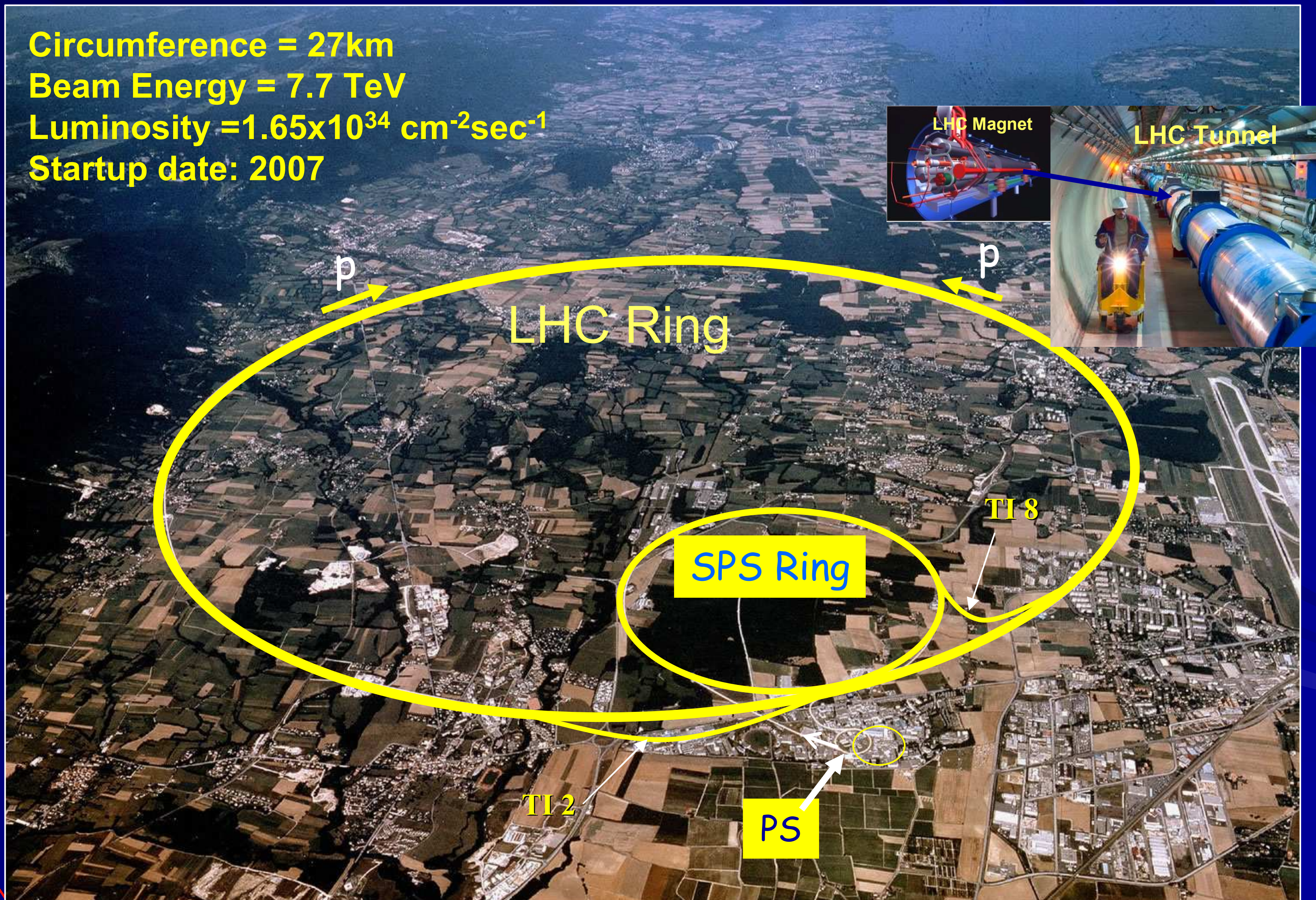


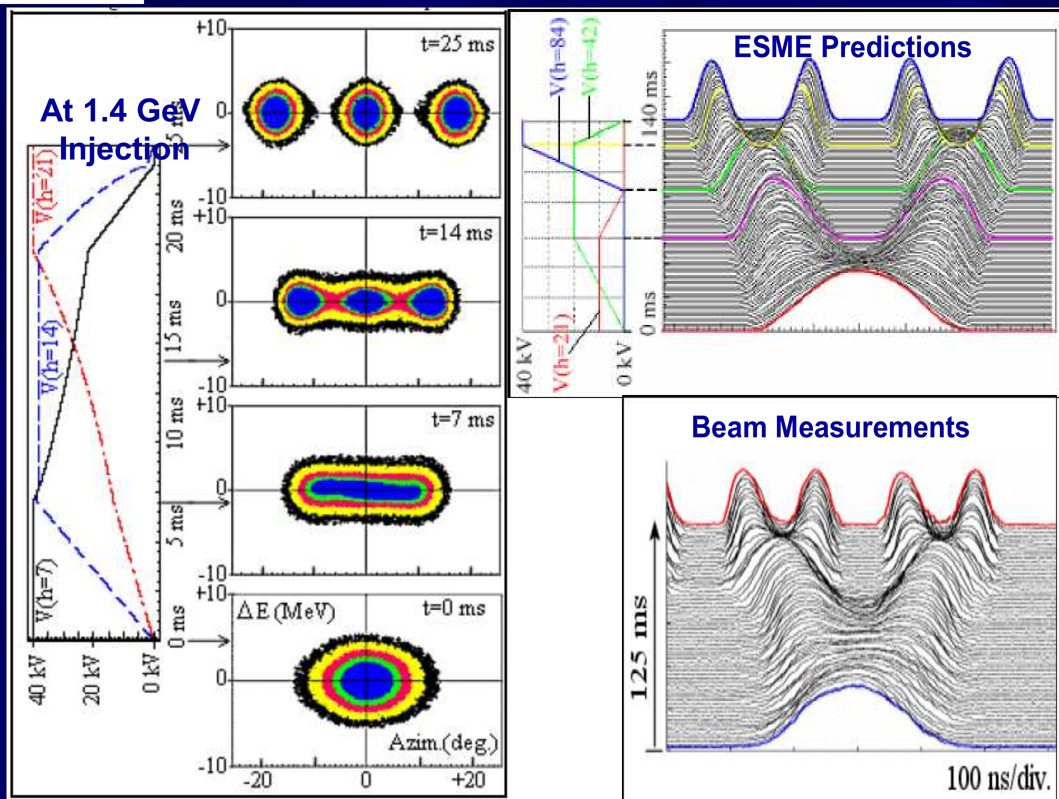

By this scheme one anticipates

- 50-100% lower longitudinal emittance proton bunches
- Better matching between p and pbar bunches
- Consequently,
  >25% increase in the collider luminosity

# CERN, LHC pp Collider
# Geneva, Switzerland



# Bright Proton Bunches for LHC




Parameters:
Number of Bunches = 2808
# of protons/bunch = 1.15-1.7x$10^{11}$
Transverse Emit. = 3.75pi-mm-mr
LE = 2.5 eVs

Bunch Splitting in the CERN PS
Each bunch is split in to 3-bunches at Injection
Further bunch double split is done at 25 GeV
6x3x2x2 = 72 bunches/injection to SPS
# of Injection from PS to SPS = 3
# of Injection from SPS to LHC = 13

# Challenges at LHC

- Design Instantaneous Luminosity
  - $10^{34}$ $cm^{-2}$ $sec^{-1}$
  - x50 of the Tevatron luminosity
- Beam-beam interactions
  - Bunch Spacing ~25 ns
  - ~16 times smaller than at the Tevatron
- Beam instability induced by electron-cloud
- Radiation issues and damage to the detectors
  - Power of the beam ~ 360MJ
  - ~x200 of Tevatron stored energy

This is Un-explored Energy Regime
There may be Many More Challenges

# Summary

- To support the HEP programs at Fermilab, we have developed many Novel Beam Manipulation Techniques that have enhanced accelerator performance. These methods can be applied at other accelerators.
- Implementation of some of these techniques for ppbar collider has resulted in world record ppbar peak Luminosity $L > 1.7 \times 10^{32} cm^{-2} sec^{-1}$ and weekly integrated luminosity $\sim 25\ pb^{-1}$

and there is more to come …

Fermilab has many Exciting Opportunities in the Collider Program before LHC turns on